



Unitized Regenerative Fuel Cell System Development

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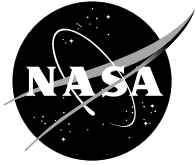
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UNITIZED REGENERATIVE FUEL CELL SYSTEM DEVELOPMENT

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ABSTRACT

Unitized Regenerative Fuel Cells (URFC) have recently been developed by several fuel cell manufacturers. These manufacturers have concentrated their efforts on the development of the cell stack technology itself, and have not up to this point devoted much effort to the design and development of the balance of plant. A fuel cell technology program at the Glenn Research Center (GRC) that has as its goal the definition and feasibility testing of the URFC system balance of plant. Besides testing the feasibility, the program also intends to minimize the system weight, volume, and parasitic power as its goal. The design concept currently being developed uses no pumps to circulate coolant or reactants, and minimizes the ancillary components to only the oxygen and hydrogen gas storage tanks, a water storage tank, a loop heat pipe to control the temperature and two pressure control devices to control the cell stack pressures during operation. The information contained in this paper describes the design and operational concepts employed in this concept. The paper also describes the NASA Glenn research program to develop this concept and test its feasibility.

INTRODUCTION

The URFC is in the process of being developed by several fuel cell manufacturers. Some of this development has been sponsored by NASA Small Business Innovative Research (SBIR) grants to Proton Energy Systems (Phase I & II, 12/1998 to 10/2001) [1],[2] and to Lynntech, Inc. (Phase I & II, 12/1999 to 11/2002) [3],[4]. Other development of the URFC by these companies and others has continued either by company internal funding or other government funding. To date, no commercial or NASA use of this technology has yet occurred.

The NASA Glenn Research Center Energetics Research Program is funding the development of a URFC system development that will use a URFC as the main component of a lightweight, compact energy storage system. The goal of this program is to demonstrate the feasibility of a URFC energy storage system that can achieve an energy density of >400 watt-hr per kg of mass. While the program does not have the funding to produce actual flight weight hardware, enough development and testing will be completed such that the >400 watt-hr per kg goal can be confidently projected. To

achieve this goal an innovative system concept was conceived and is the subject material of this paper. Ancillary components supporting this system concept, as well as supporting other fuel cell and electrolysis systems are being developed, and will be the subject of future papers.

The applications for this technology are the same as for Regenerative Fuel Cell (RFC) systems. NASA applications include high altitude airships [5], lunar or Mars-based outposts, and other secondary battery applications where the discharge period is 1 to 2 hours long or longer.

BACKGROUND

The URFC's developed to date are all based on the Proton Exchange Membrane (PEM). The key advantage of the URFC over other RFC systems is that the URFC does both the process of electrolysis of water as well as the process of recombining of the hydrogen and oxygen gas to produce electricity. Because of this, only one cell stack is needed instead of one electrolysis cell stack and one fuel cell stack. This saves a substantial amount of weight since the cell stacks are the major components of a RFC system. Besides saving the weight of one cell stack, the plumbing, wiring and ancillary equipment for one cell stack is also eliminated. The operation of the URFC system is also simpler. A RFC requires that when the fuel cell stack is active, the electrolysis cell stack must be kept warm to avoid freezing water lines and transient warm-up periods. Likewise, as the electrolysis cell stack is active, the fuel cell stack must be kept warm to avoid freezing water lines, excessive condensation, and transient warm-up periods. Maintaining cell stacks in standby conditions complicates the overall system design, resulting in greater mass, volume, and parasitic power.

Early efforts to develop a reversible cell resulted in cells with poor performance or cells not easily reversed in their operation. The URFCs developed as a result of the SBIR grants have performance approaching that of dedicated fuel cells and electrolysis cells. Dedicated fuel cells or electrolysis cells often have the reactants circulated through the cell stack. Usually this is done to remove the products of the reaction (product water during fuel cell operation, and product gases during electrolysis cell operation). Sometimes the reactants are also circulated for cooling of the cell stack during its operation. For a URFC to act without circulation pumps

require that the reactants not be circulated through the cell stack, but instead, be “dead-ended” into the cell stack.

As an energy storage system, the URFC system “charges” and “discharges” like a rechargeable battery. While charging, the URFC operates the electrolysis process, which splits water into hydrogen and oxygen. While discharging, the URFC operates the fuel cell process, which combines hydrogen and oxygen and produces electricity.

The gases produced during electrolysis are expelled from the cell stack by the production of still more gas inside the cell stack. The continued production of gases by the cell stack pushes the gases into the reactant storage tanks, gradually “pumping” the gases to higher and higher pressure where they are stored. In addition to the oxygen and hydrogen, a certain level of water vapor also accompanies these gases when they are expelled from the cell stack.

During the URFC fuel cell process, as gases are consumed inside the cell stack, more gas is delivered to the cell stack by the pressurized reactant storage tanks. The water formed inside of the URFC is removed by either the capillary action of wicking material that is in close proximity to the active electrode sites or pressure differentials inside the cell stack. The water is pushed out of the cell by a pressure difference between the water pressure inside the cell stack and the water pressure inside an external water storage tank.

The management of reactants inside the URFC cell stack is highly influenced by both the materials and the construction inside the cell stack. Besides the development of the reversible electrodes, proper and reliable reactant management inside the cell stack is most important to achieving acceptable URFC performance. Achieving this level of reactant management inside the cell stack during both electrolysis and fuel cell operation, and the transitions between these different processes is currently the single biggest hurdle yet to be accomplished. Figures 1 and 2 are photographs of URFCs recently developed by Proton Energy Systems and Lynntech, Inc.



Figure 1 Proton Energy Systems URFC Stack [2]



Figure 2 Lynntech, Inc. 8-Cell 200cm² URFC Stack [4]

URFC System Concept

Figure 3 shows a schematic of the URFC system described in this paper. The system consists of the URFC stack, a gas storage system, pressure controls between the URFC stack and the gas storage system, a water storage tank, a heat pipe thermal control system, and a power/system control interface.

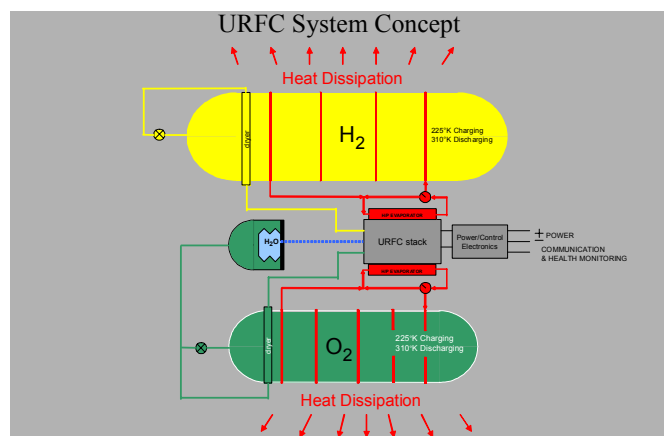


Figure 3 URFC Schematic

The ambient environment is quite cold for the applications the URFC system is envisioned to operate in such as in space or at high atmospheric altitudes. Typically the ambient temperature would be -40°C or colder.

ELECTROLYSIS OPERATION

The following sections describe the operation of the URFC system during the electrolysis (charging) portion of the energy storage cycle.

ELECTROLYSIS—O₂ During the electrolysis process oxygen is produced inside the URFC stack. A mixture of oxygen and water vapor that is in equilibrium with the temperature and pressure of the URFC stack exits the URFC stack and into a section of tubing that is wrapped around the oxygen storage tank. This section of tubing (called the oxygen regenerative dryer) is in close thermal contact with the surface of the oxygen tank. As the oxygen water vapor mixture flows through this section of tubing, heat from the gas mixture is transferred to the surface of the oxygen tank. The loss of energy from the oxygen mixture causes the water vapor in the mixture to condense and/or freeze on the inside wall of the oxygen regenerative dryer. The water that is separated from the gas phase remains inside the dryer tubing while the dried oxygen eventually makes its way to the pressure dome of the water storage tank and to the bi-directional oxygen pressure control. The bi-directional pressure control acts as a backpressure regulator that controls the oxygen pressure inside the URFC and water tank pressure dome and allows this pressure to gradually increase all the while keeping this pressure within user-defined limits with respect to the hydrogen pressure inside the URFC stack. The dried oxygen that passes through the bi-directional pressure control enters the oxygen storage where it gradually accumulates until needed during the discharge cycle of operation. This process continues until either the charging energy is stopped, the oxygen tank reaches its maximum pressure, or the water tank reaches its minimum level.

ELECTROLYSIS—H₂ During the electrolysis process hydrogen is also produced inside the URFC stack. A mixture of hydrogen and water vapor that is in equilibrium with the temperature and pressure of the URFC stack exits the URFC stack and into a section of tubing that is wrapped around the hydrogen storage tank. This section of tubing (called the hydrogen regenerative dryer) is in close thermal contact with the surface of the hydrogen tank. As the hydrogen water vapor mixture flows through this section of tubing, heat from the gas mixture is transferred to the surface of the hydrogen tank. The loss of energy from the hydrogen mixture causes the water vapor in the mixture to condense and/or freeze on the inside wall of the hydrogen regenerative dryer. The water that is separated from the gas phase remains inside the dryer tubing while the dried hydrogen eventually makes its way to the bi-directional hydrogen pressure control. The bi-directional pressure control acts as a backpressure regulator that controls the hydrogen pressure inside the URFC and allows this pressure to gradually increase all the while keeping this pressure within user-defined limits with respect to the oxygen pressure inside the URFC stack. The dried hydrogen that passes through the bi-directional pressure control enters the hydrogen storage where it gradually accumulates until needed during the discharge cycle of operation. This process continues until either the charging energy is stopped, the hydrogen tank reaches its maximum pressure, or the water tank reaches its minimum level.

ELECTROLYSIS—H₂O During electrolysis the URFC electrolyzes water. As the water is consumed, the URFC draws in water from an external water storage tank by a siphon-like action. The water storage tank consists of a bellows inside a pressure dome. The bellows has a spring-like action that, left unrestrained, would cause the bellows to expand to nearly the entire volume of the pressure dome. The water is stored inside the bellows. Outside the bellows, but inside the pressure dome, oxygen is present. This arrangement allows the water volume inside the bellows to expand or contract as needed all the while keeping the water pressure slightly less than the oxygen pressure that exists outside the bellows. It is vitally important to maintain the water pressure slightly below the oxygen pressure, because this pressure difference is what keeps liquid water separated from the oxygen and hydrogen gas inside the URFC stack.

ELECTROLYSIS—THERMAL CONTROL SYSTEM One of the key features of the URFC system is the heat pipe thermal control system. During electrolysis, the waste heat produced by the URFC cell stack is transferred to the heat pipe system. Bypass valves in the heat pipe system allow the heat pipe fluid to bypass the heat radiating surfaces of oxygen and hydrogen storage tank when the URFC is not at optimum operating temperature. Once the URFC stack is at its operating temperature, the heat pipe fluid flows through heat pipes that are wrapped around the oxygen and hydrogen storage tanks. The heat pipes are in close thermal contact with the gas storage tank surface and as the heat pipe fluid flows through the tubing wrapped around the tanks, heat is transferred from the heat pipe system to the surface of the gas storage tanks. The tank walls, acting as a heat fins, spread this waste heat across the entire tank surface of both the oxygen and hydrogen storage tanks. The tank surfaces also radiate this heat to the freezing cold environment. Because the amount of waste heat produced during electrolysis is small per unit area over which that heat is spread, the tank surface temperature of both the oxygen and hydrogen storage tanks drops below 0 °C.

ELECTROLYSIS—POWER AND CONTROL The power control of the URFC system matches the voltage of the electrical power source to the required voltage needed by the URFC stack for electrolysis. A computer system control provides the software control of the pressure controls as well as the health monitoring and communications.

FUEL CELL OPERATION

The following sections describe the operation of the URFC system during the fuel cell operation (discharging) portion of the energy storage cycle.

FUEL CELL OPERATION—O₂ During the fuel cell process oxygen is consumed inside the URFC stack. As oxygen is consumed, the oxygen pressure inside the URFC stack and

inside the water tank pressure dome is reduced from the pressure achieved during the previous electrolysis operation. The URFC stack oxygen pressure continues to fall until the pressure is at the steady-state fuel cell operating pressure (about 50 psi). Once at this pressure, oxygen flows from the oxygen storage tank as needed to maintain the steady-state fuel cell operating pressure. The oxygen flows from the water tank pressure dome and from the oxygen storage tank through the oxygen regenerative dryer on its way to the URFC stack. As the oxygen flows through the regenerative dryer, the gas absorbs heat and water vapor from the inside surface of the dryer tube. The dryer tube is in turn warmed by the tank surface that is attempting to radiate the substantially higher amount of waste heat generated during the fuel cell operation. Due to the lower pressure and warm temperature, the oxygen gas, as it flows back to the URFC stack, eventually evaporates all of the water previously trapped on the wall of the dryer tube during the electrolysis process. In doing so, the dryer tube is "regenerated" and ready for the next electrolysis phase. During the fuel cell operation the bi-directional pressure control acts as a forward, or pressure reducing, regulator that controls the oxygen pressure inside the URFC stack and water tank pressure dome and allows this pressure to gradually decrease to the steady-state fuel cell operating pressure. The bi-directional pressure regulator does this while keeping the URFC stack oxygen pressure within prescribed limits with respect to the hydrogen pressure inside the URFC stack. The fuel cell operation continues as long as electrical energy is withdrawn from the URFC system or until the oxygen storage tank falls below its minimum pressure or the water storage tank reaches its maximum filled state.

FUEL CELL OPERATION—H₂ During the fuel cell process hydrogen is consumed inside the URFC stack. As hydrogen is consumed the hydrogen pressure inside the URFC stack is reduced from the pressure achieved during the previous electrolysis operation. The URFC stack hydrogen pressure continues to fall until the pressure is at the steady-state fuel cell operating pressure (about 50 psi). Once at this pressure, hydrogen flows from the hydrogen storage tank as needed to maintain the steady-state fuel cell operating pressure. The hydrogen flows from the hydrogen storage tank through the hydrogen regenerative dryer on its way to the URFC stack. As the hydrogen flows through the regenerative dryer, the gas absorbs heat and water vapor from the inside surface of the dryer tube. The dryer tube is in turn warmed by the tank surface that is attempting to radiate the substantially higher amount of waste heat generated during the fuel cell operation. Due to the lower pressure and warm temperature, the hydrogen gas, as it flows back to the URFC stack, eventually evaporates all of the water previously trapped on the wall of the dryer tube during the electrolysis process. In doing so, the dryer tube is "regenerated" and ready for the next electrolysis phase. During the fuel cell operation the bi-directional pressure control acts as a forward, (pressure reducing), regulator that controls the hydrogen pressure inside

the URFC stack and allows this pressure to gradually decrease to the steady-state fuel cell operating pressure. The bi-directional pressure regulator does this while keeping the URFC stack hydrogen pressure within prescribed limits with respect to the oxygen pressure inside the URFC stack. The fuel cell operation continues as long as electrical energy is withdrawn from the URFC system or until the hydrogen storage tank falls below its minimum pressure or the water storage tank reaches its maximum filled state.

FUEL CELL OPERATION—H₂O During fuel cell operation the URFC produces water. As the water is produced, the water cavities inside the URFC stack suck in the water. The water is eventually sucked all the way back into the water storage tank by a siphon-like action. The water storage tank bellows spring-like action ensures that this suction is always present regardless of how full the water tank is.

FUEL CELL OPERATION—THERMAL CONTROL SYSTEM During fuel cell operation, the waste heat produced by the URFC cell stack is transferred to the heat pipe system. Bypass valves in the heat pipe system allows the heat pipe fluid to bypass the heat radiating surfaces of oxygen and hydrogen storage tank when the URFC is not at its optimum operating temperature. Once the URFC stack is at its operating temperature, the heat pipe fluid flows through heat pipes that are wrapped around the oxygen and hydrogen storage tanks. The heat pipes are in close thermal contact with the gas storage tank surface and as the heat pipe fluid flows through the tubing wrapped around the tanks heat is transferred from the heat pipe system to the surface of the gas storage tanks. The tank walls, acting as a heat fins, spread this waste heat across the entire tank surface of both the oxygen and hydrogen storage tanks. The tank surfaces also radiate this heat to the freezing cold environment. Because the amount of waste heat produced during fuel cell operation is large per unit area over which that heat is spread, the tank surface temperature of both the oxygen and hydrogen storage tanks goes to well above freezing temperatures.

FUEL CELL OPERATION—POWER AND CONTROL The power control of the URFC system matches the required voltage of the electrical loads being supplied by the URFC system. A computer system control provides the software control of the pressure controls as well as the health monitoring and communications.

STORAGE TANK/RADIATOR ANALYSIS

As was described earlier, the amount of heat per unit of radiator area is smaller during the charge phase of the URFC system operation than during the discharge phase operation. The effect of this is to produce freezing storage tank surface temperatures during the charge phase and above freezing temperatures during the discharge phase. The following analysis is provided to further describe this phenomenon and

the URFC system design parameters that influence its magnitude.

The Stefan - Boltzmann Law states that,

$$\frac{Q}{A} = e\sigma(T^4 - T_E^4) \quad (1)$$

Where

- Q = Heat radiation rate, watt
- A = Heat radiation area, m²
- e = Emissivity, %
- σ = 5.6703 × 10⁻⁸ watt-m²-K⁻⁴
- T = Temperature of radiating body, K
- T_E = Temperature of surrounding environment, K

Using equation (1) to describe the heat radiation during URFC system charging,

$$\frac{Q_C}{A_T} = e\sigma(T_C^4 - T_E^4) \quad (2)$$

Where

- Q_C = Heat radiation rate during charging, watt
- A_T = Total tank surface area, m²
- T_C = Tank surface temperature during charging, K

Similarly, the heat radiation during URFC system discharging can be expressed as,

$$\frac{Q_D}{A_T} = e\sigma(T_D^4 - T_E^4) \quad (3)$$

Where

- Q_D = Heat radiation rate during discharging, watt
- T_D = Tank surface temperature during discharging, K

The heat radiation rate during charging and during discharging can be expressed as,

$$Q_C = (1 - \eta_C)\xi_C \quad (4)$$

$$Q_D = (1 - \eta_D)\xi_D \quad (5)$$

Where

- η_C = Energy efficiency during charging, watt
- η_D = Energy efficiency during discharging, watt
- ξ_C = Theoretical power required during charging, watt
- ξ_D = Theoretical discharge power produced, watt

Based on the higher heating value of hydrogen of 4405 watt-hr per kg of water produced, the average theoretical power during charging and discharging is:

$$\xi_C = 4405 M_{wtC}^{-1} \quad (6)$$

$$\xi_D = 4405 M_{wtD}^{-1} \quad (7)$$

Where

- M_w = Mass of water used or produced, kg
- t_C = Charging time, hour
- t_D = Discharging time, hour

The heat dissipation area is the combined surface area of the oxygen and hydrogen storage tanks.

$$A_T = A_O + A_H \quad (8)$$

Where

- A_O = Oxygen tank surface area, m²
- A_H = Hydrogen tank surface area, m²

Substituting Equations (4), (6), and (8) into Equation (2) to get an expression for the storage tank surface temperature during the charging phase,

$$\frac{(1 - \eta_C) 4405 M_{wtC}^{-1}}{A_O + A_H} = e\sigma(T_C^4 - T_E^4) \quad (9)$$

Likewise substituting Equation (5), (7), and (8) into Equation (3) to get an expression for the storage tank surface temperature during the discharging phase,

$$\frac{(1 - \eta_D) 4405 M_{wtD}^{-1}}{A_O + A_H} = e\sigma(T_D^4 - T_E^4) \quad (10)$$

The surface area of each gas storage tank can be expressed as the ratio of surface area to volume multiplied by the volume,

$$A_O = (A_O V_O^{-1}) V_O \quad (11)$$

$$A_H = (A_H V_H^{-1}) V_H \quad (12)$$

Where

- V_O = Oxygen tank volume, m³
- V_H = Hydrogen tank volume, m³

For cylindrical tanks with spherical heads such as shown in Figure 4, the ratio of the storage tank surface area to volume can be expressed as,

$$AV^{-1} = \frac{2}{r - (2/3)(r^2/L)} \quad (13)$$

Where

- r = Tank radius, m
- L = Tank volume, m³

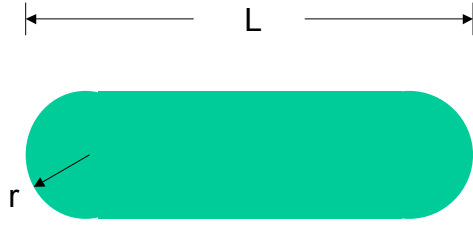


Figure 4 URFC System Gas Storage Tank

Equation (13) is plotted in Figure 5. As the tank gets more and more spherical ($r/L \rightarrow 1/2$) the AV^{-1} ratio approaches a value of $3/r$. As the tank gets less and less spherical ($r/L \rightarrow 0$) the AV^{-1} ratio approaches a value of $2/r$.

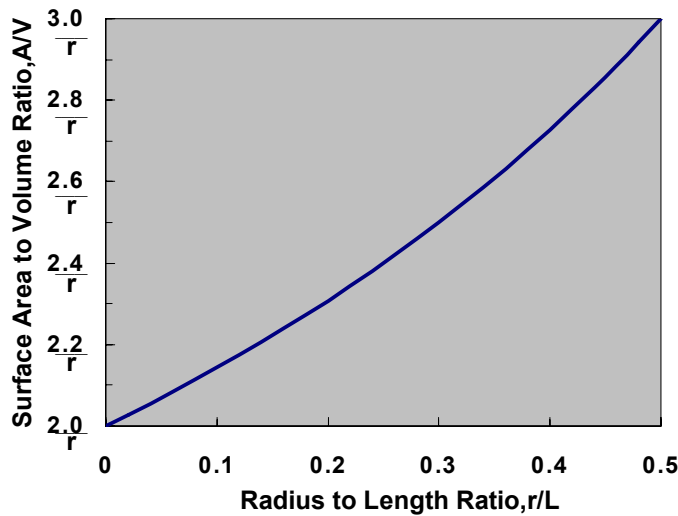


Figure 5 Tank Surface:Volume Ratio vs Radius:Length Ratio

Substituting Equation (11) and (12), into equations (9) and (10), and assuming that the oxygen and hydrogen tanks have identical AV^{-1} ratios, the heat radiation expression during the charge and discharge phase can be expressed as,

$$\frac{(1 - \eta_C) 4405 M_{wtC}^{-1}}{AV^{-1} (V_O + V_H)} = e\sigma(T_C^4 - T_E^4) \quad (14)$$

$$\frac{(1 - \eta_D) 4405 M_{wtD}^{-1}}{AV^{-1} (V_O + V_H)} = e\sigma(T_D^4 - T_E^4) \quad (15)$$

The volume of the oxygen and hydrogen storage tanks can be expressed as,

$$V_O = \frac{n_O RT_O}{P_O} \quad (16)$$

$$V_H = \frac{n_H RT_H}{P_H} \quad (17)$$

Where

- n_O = Moles of oxygen, gmols
- n_H = Moles of hydrogen, gmols
- T_O = Temperature of oxygen, K
- T_H = Temperature of hydrogen, K
- P_O = Pressure of oxygen, atm
- P_H = Pressure of hydrogen, atm
- R = 8.2×10^{-5} , atm-m³-gmole⁻¹-K⁻¹

The volumes of the gas storage tanks don't change during operation of the URFC, and are sized to accommodate the mass of each gas stored at the peak level of charge. Under these conditions, it is assumed that the peak charge pressure is approximately the same for both oxygen and hydrogen. It is also assumed that, at peak charge, the oxygen gas temperature is approximately the same as the hydrogen gas temperature for this sizing calculation, and that these temperatures are also equal to the surface temperature of the gas storage tanks during charging of the URFC. Using these assumptions, Equation (14) and (15) can be rewritten as,

$$\frac{(1 - \eta_C) 4405 M_{wtC}^{-1}}{A V^{-1} R T_C P_C^{-1} (n_O + n_H)} = e\sigma(T_C^4 - T_E^4) \quad (18)$$

$$\frac{(1 - \eta_D) 4405 M_{wtD}^{-1}}{A V^{-1} R T_D P_C^{-1} (n_O + n_H)} = e\sigma(T_D^4 - T_E^4) \quad (19)$$

Where

- P_C = Peak charge pressure, atm

It should be noted that the denominators on the left-hand side of equations (18) and (19) are constants and equal to each other (the combined surface area of the tanks does not change from charge to discharge once the tanks have been sized).

The moles of oxygen and hydrogen can be expressed as,

$$n_O + n_H = 1.5 n_W \quad (20)$$

Where

- n_W = mass of water used or produced, gmols

The moles of water can be expressed as,

$$n_W = \frac{M_W}{.018} \quad (21)$$

Substituting equations (20) and (21) into equations (18) and (19) yields,

$$\frac{(1 - \eta_C) 4405 M_{wtC}^{-1}}{AV^{-1}RT_C P_C^{-1}(1.5M_W/.018)} = e\sigma(T_C^4 - T_E^4) \quad (22)$$

$$\frac{(1 - \eta_D) 4405 M_{wtD}^{-1}}{AV^{-1}RT_C P_C^{-1}(1.5M_W/.018)} = e\sigma(T_D^4 - T_E^4) \quad (23)$$

Simplifying equations (22) and (23)

$$\frac{(1 - \eta_C) 4405 t_C^{-1} (.012)}{AV^{-1}RP_C^{-1}T_C} = e\sigma(T_C^4 - T_E^4) \quad (24)$$

$$\frac{(1 - \eta_D) 4405 t_D^{-1} (.012)}{AV^{-1}RP_C^{-1}T_C} = e\sigma(T_D^4 - T_E^4) \quad (25)$$

Equation (24) is plotted as the tank surface temperature during the charge phase versus the charge energy efficiency in Figures 6, 7, and 8. Figure 6 holds the peak charge pressure and the charging time constant, and plots equation (24) using different A V⁻¹ ratios.

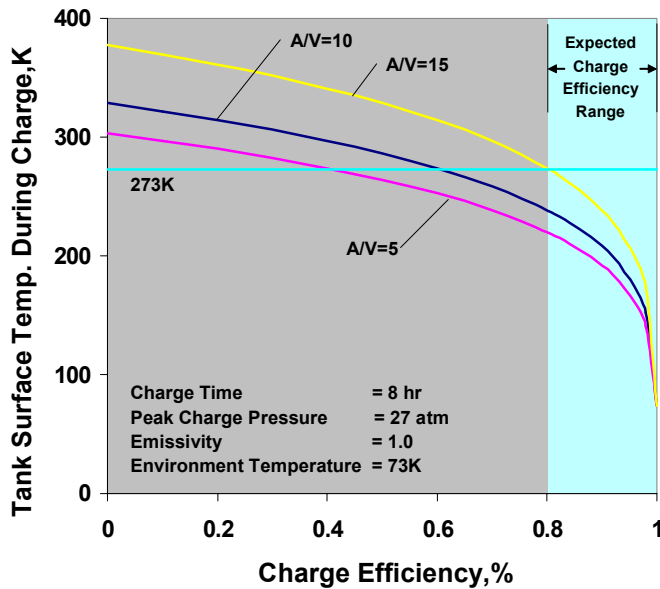


Figure 6 Tank Surface Temperature vs Charge Efficiency

Figure 7 holds the AV⁻¹ ratio and the charging time constant, and plots equation (24) using different peak charge pressures.

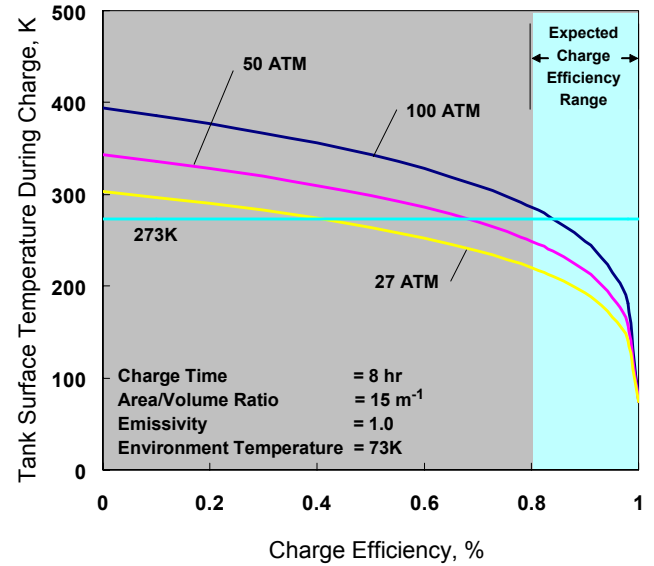


Figure 7 Tank Surface Temperature vs Charge Efficiency

Figure 8 holds the AV⁻¹ ratio and the peak charge pressure constant, and plots equation (24) using different charging times. In each plot the expected range of charge phase energy efficiency is highlighted. The freezing point of water is also marked. Figures 6, 7, and 8 show that within the expected charge efficiency range and the range of tank A/V, discharge time, and peak charge pressure, the surface temperature of the storage tanks during charging generally stay below freezing.

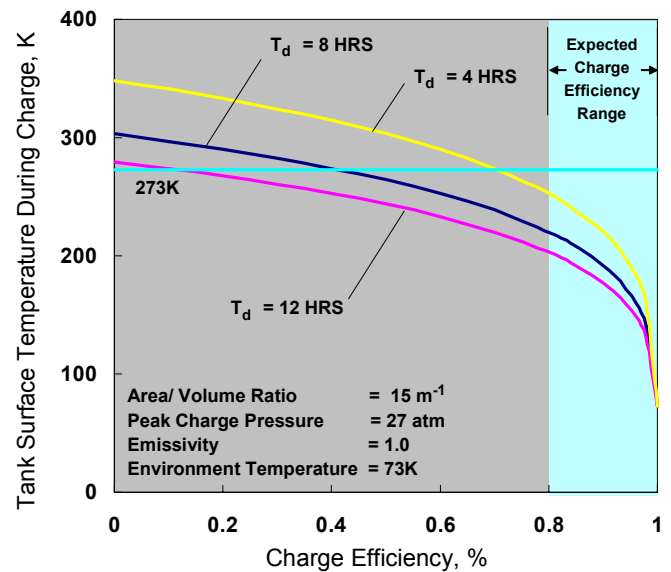


Figure 8 Tank Surface Temperature vs Charge Efficiency

Equation (25) is plotted as the tank surface temperature during the discharge phase versus the discharge energy efficiency in Figure 9, 10, and 11. Figure 9 holds peak charge pressure and the discharging time constant, and plots equation (24) using different AV^{-1} ratios.

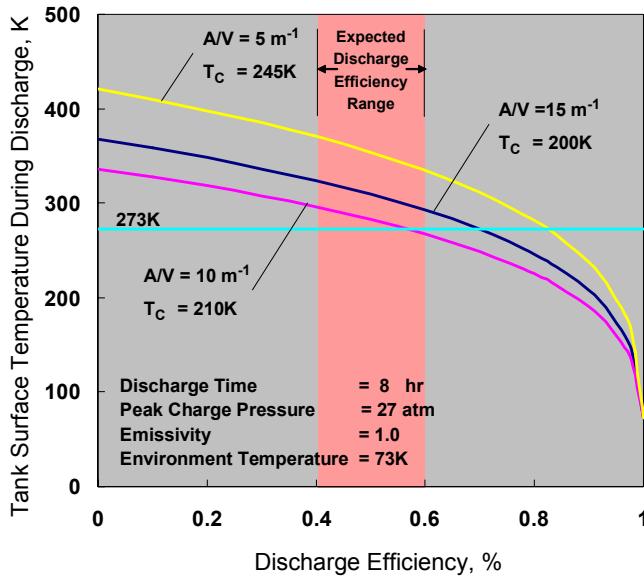


Figure 9 Tank Surface Temperature vs Discharge Efficiency

Figure 10 holds the AV^{-1} ratio and the discharging time constant, and plots equation (24) using different peak charge pressures.

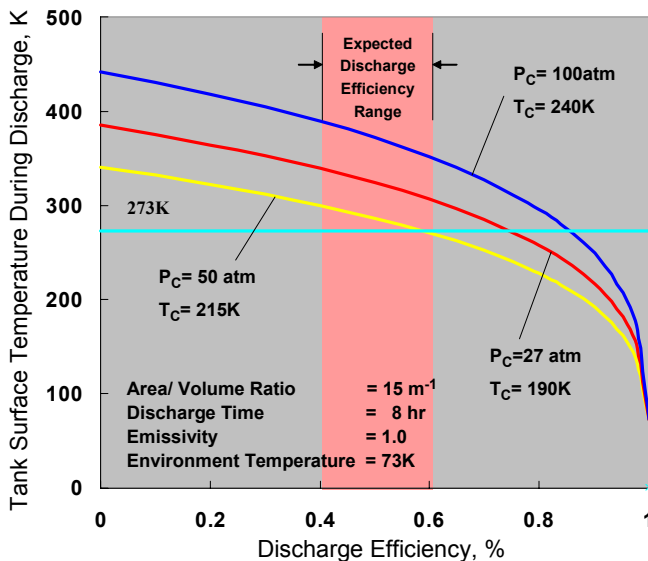


Figure 10 Tank Surface Temperature vs Discharge Efficiency

Figure 11 holds the AV^{-1} ratio and the peak charge pressure constant, and plots equation (24) using different discharging times. In each plot the expected range of discharge phase energy efficiency is highlighted. The freezing point of water is also marked. Figures 9, 10, and 11 show that within the expected discharge efficiency range and the range of tank A/V , discharge time, and peak charge pressure, the surface temperature of the gas storage tanks during discharging stay above freezing.

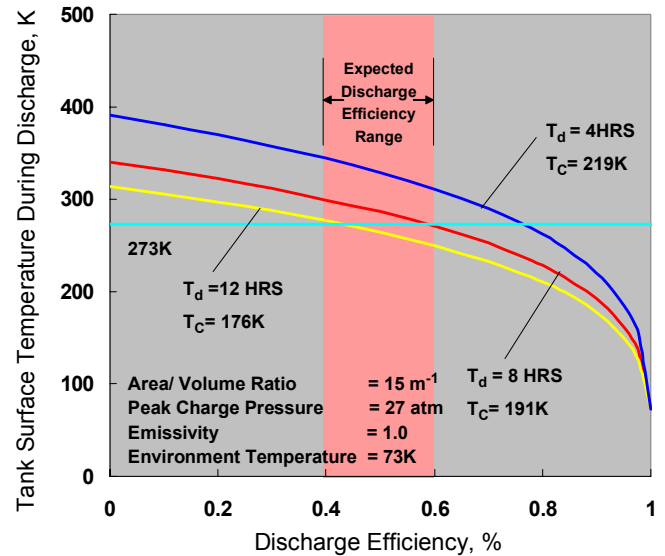


Figure 11 Tank Surface Temperature vs Discharge Efficiency

Figure 12 shows both a charge and discharge curve versus efficiency. Figure 12 shows that for a system with a 12/12 hour charge/discharge where the peak charge pressure is 27

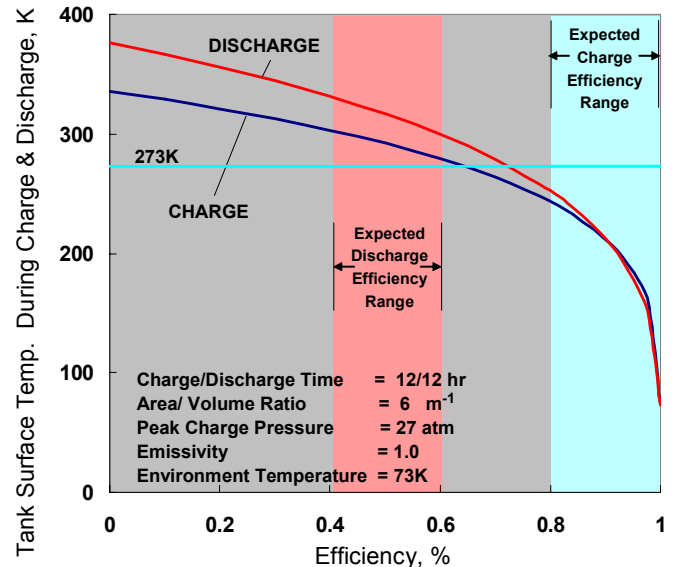


Figure 12 Tank Surface Temperature vs Efficiency

atmosphere (400 psia), during charging the surface temperature of the tanks is well below the freezing temperature, whereas during the discharge phase the tank surface temperature is well above freezing.

REGENERATIVE FUEL CELL TECHNOLOGY PROGRAM

The Regenerative Fuel Cell Technology Program at the Glenn Research Center has as its goal the evaluation of the feasibility of the system concept described within this paper and the development of the ancillary equipment used by this system concept. The ancillary components being developed are the gas storage tanks with integral heat pipes and gas dryers, bi-directional pressure controllers, a water storage tank, and the heat pipe interface to the URFC stack. A system level test within a thermal vacuum chamber is planned for 2005.

CONCLUSION

The regenerative fuel cell concept described in this paper is a very simplified approach.. This approach minimizes system components to "bare essentials," eliminating to a great extent any ancillary equipment that would add unnecessary mass, volume and parasitic power usage. The analysis of the gas storage tanks as thermal control surfaces appears feasible and also allows for the management of water within the oxygen and hydrogen gas streams as the gases travel back and forth between the gas storage tanks and the URFC stack. The anticipated result of the development of the URFC stack technology coupled with development of the system architecture and ancillary components is an energy storage system that will maximize the energy density of the URFC system.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

GRC	Glenn Research Center
H ₂	Hydrogen
H ₂ O	Water
NASA	National Aeronautics and Space Administration
O ₂	Oxygen
RFC	Regenerative Fuel Cell
SBIR	Small Business Innovative Research
URFC	Unitized Regenerative Fuel Cells

A	= Heat radiation area, m ²
A _H	= Hydrogen tank surface area, m ²
A _O	= Oxygen tank surface area, m ²
A _T	= Total tank surface area, m ²
e	= Emissivity, %
L	= Tank volume, m ³
M _W	= Mass of water used/produced, kg
n _H	= Gmole of hydrogen, gmole
n _O	= Gmole of oxygen, gmole

n _W	= Moles of water used/produced, gmole
σ	= 5.6703 × 10 ⁻⁸ watt-m ² -K ⁻⁴
t _C	= Charging time, hour
t _D	= Discharging time, hour
T	= Temperature of radiating body, K
T _C	= Surface temperature of tanks during charging, K
T _D	= Surface temperature of tanks during discharging, K
T _E	= Temperature of surrounding environment, K
P _C	= Peak charge pressure, atm
P _H	= Pressure of hydrogen, atm
P _O	= Pressure of oxygen, atm
Q	= Heat radiation rate, watt
Q _C	= Heat radiation rate during charging, watt
Q _D	= Heat radiation rate during discharging, watt
r	= Tank radius, m
R	= 8.2 × 10 ⁻⁵ , atm-m ³ -gmole ⁻¹ -K ⁻¹
T _H	= Temperature of hydrogen, K
T _O	= Temperature of oxygen, K
V _H	= Hydrogen tank volume, m ³
V _O	= Oxygen tank volume, m ³
η _C	= Energy efficiency during charging, watt
η _D	= Energy efficiency during discharging, watt
ξ _C	= Theoretical power required during charging, watt
ξ _D	= Theoretical power produced during discharging, watt

REFERENCES

- [1] Zero Gravity – PEM Regenerative Fuel Cell Energy Storage System. Principal Investigator- Trent Molter, Proton Energy Systems, Inc. 50 Inwood Road Rocky Hill, CT 04067, SBIR Phase I Final Report, Contract No. NAS3 99042, June 22, 1999.
- [2] Zero Gravity – PEM Regenerative Fuel Cell Energy Storage System. Principal Investigator – Trent Molter, Proton Energy Systems, Inc. 50 Inwood Road Rocky Hill, CT 04067, SBIR Phase II Final Report, Contract No. NAS3 00013, Oct. 25, 2001.
- [3] A Unitized Regenerative PEM Fuel Cell Energy Storage System, Principal Investigators – Alan Cisar and Eric Clarke, Lynntech, Inc. 7610 Eastmark Dr., College Station, TX 77840, SBIR Phase I Final Report, Contract No. NAS4-00012, June 8, 2000.
- [4] A Unitized Regenerative PEM Fuel Cell Energy Storage System, Principal Investigators – Brad Fiebig, Jeremy Steinshneider, James Layton, Carlos Salinas, Alan Cisar, Lynntech, Inc. 7610 Eastmark Dr., College Station, TX 77840, SBIR Phase II Final Report, Contract No. NAS4-01006, January 31, 2003.
- [5] Kenneth A. Burke, "High Energy Density Regenerative Fuel Cell Systems for Terrestrial Applications," NASA/TM—1999-209429, SAE 00-01-2600, July 1999.

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